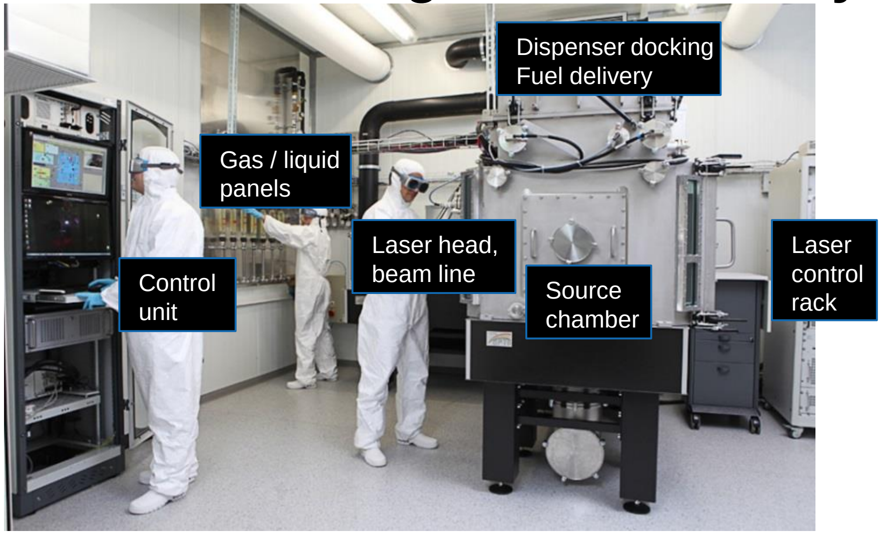
Laser induced shockwave droplet breakup dynamics

Duane Hudgins, Alex Nieland and Reza S. Abhari
Swiss Federal Institute of Technology Zurich, Sonneggstrasse 3, CH-8092 Zurich, Switzerland.

Presentation Outline

- Neutral Cluster Dynamics
- Model Description
  - VOF Geometry and Numerical Methods
  - Initial Conditions
- Simulations Results Overview
- Droplet Fragmentation Analytical Model
- Comparison with Experimental Results
- Conclusions

ALPS II EUV Light Source – Key Numbers

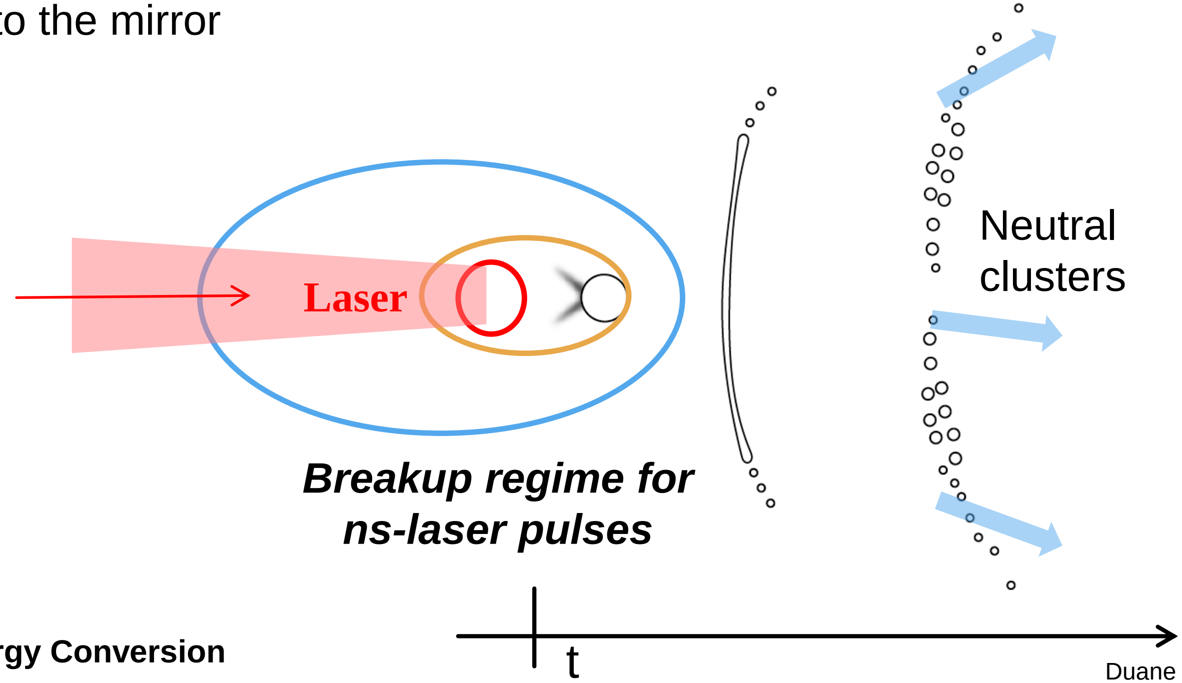


Parameters	Value
Laser power on target (W)	1400
Laser frequency (kHz)	>8
Laser focal spot size (µm)	70 (FWHM)
EUV source size (µm)	60 (FWHM)
Conversion efficiency (%)	>1%
Source power at the source (W)	>12
Source brightness (W/mm^{2}sr)	350

- Driven by DPSS Nd:YAG laser (average power of 1.4 kW, 1.064 µm, 8-20 kHz).
- 6th generation in-house droplet dispenser >30 µm tin droplet generation for hours of operation.
- Droplet tracking system with laser triggering on individual droplets enables droplet-laser alignment within <10% of droplet diameter.
- Full diagnostic including in-band energy monitors and out-of-band spectroscopy
- Debris mitigated grazing incidence collector, including clean IF module with imaging capability.
- Compatible with various collector configurations

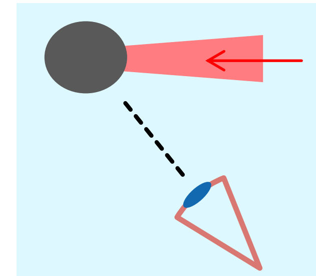
Work goal is to predict size and distribution of neutral clusters

- Majority of droplet and plasma debris mass are *neutral clusters*
  - Neutral clusters are the liquid droplet fragments ejected away from the plasma region
  - This work is focused on predicting the formation and distribution of neutral clusters
  - Unablated droplet is flattened into a liquid sheet and then breaks into small droplets
  - Plasma formation and expansion occurs within 30-40 ns, liquid deformation timescale is on the order of > 1µs
- Splashes can affect ML collector mirror through direct impact and/or bouncing on one surface onto the mirror



Breakup regime for ns-laser pulses

Volume of Fluid CFD Model with Moving Domain

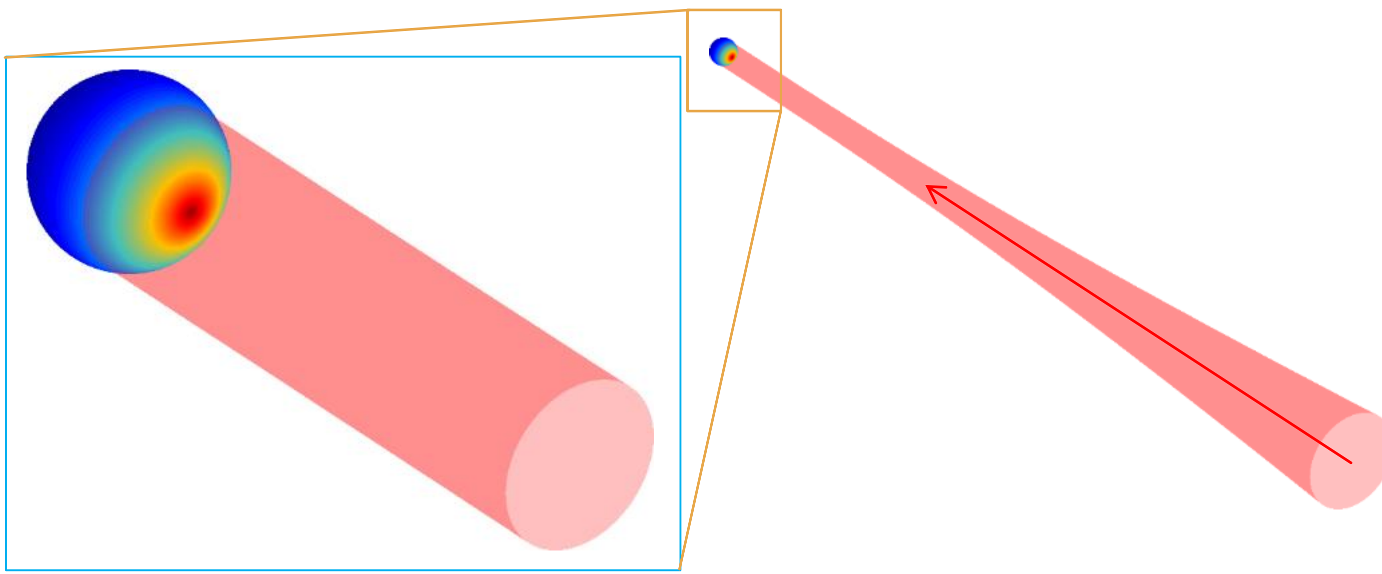


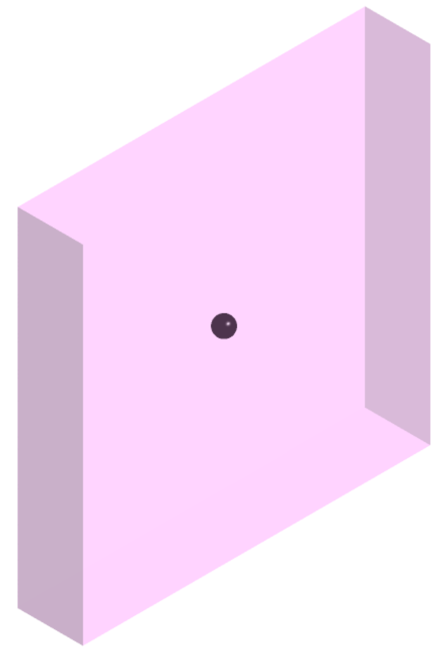
Simulation Setup

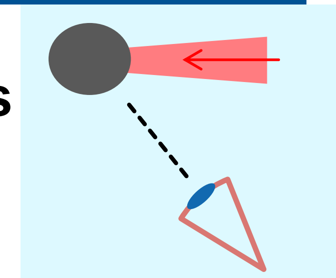
- Run in Fluent 18.0
- Volume of Fluid (VOF) model with Coupled Level-Set Method
- Geo-reconstruct scheme

Domain Geometry

- Moving Reference Frame
- Droplet initialized in center of the rectangular cuboid domain
- Cuboid wall boundary conditions set to constant pressure outlet





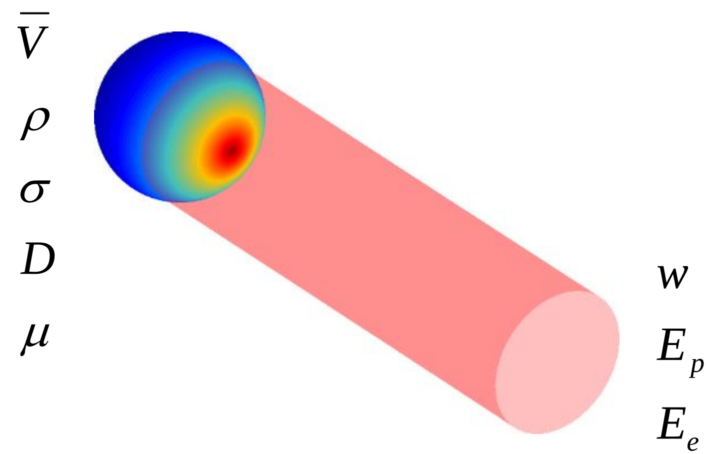


Six cases were simulated over a range of pulse energies

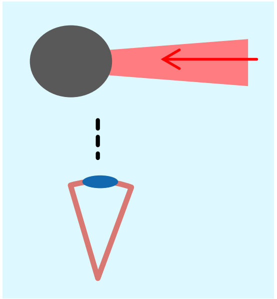
- *We* = 120 - 15’000
- *Re* = 5’900 – 62’000
- E_e* = 78 – 800
- log10(E_p*) = 5.4 – 7.5
- *w/D* = 0.41 – 0.97

$$E_e^* = E_e \sqrt{\frac{\rho D^3}{\sigma^3}} \qquad E_p^* = \frac{E_p}{D^2 \sigma}$$

- *w* = 1/e² beam waist radius
- E_p = laser pulse energy
- E_e = laser pulse irradiance
- $\bar{V}$ = mean radial neutral cluster velocity
- *ρ* = density
- *D* = droplet diameter
- *ρ* = density
- *σ* = surface tension
- μ = dynamic viscosity



Expanding ablated material transfers momentum to remaining droplet fluid*

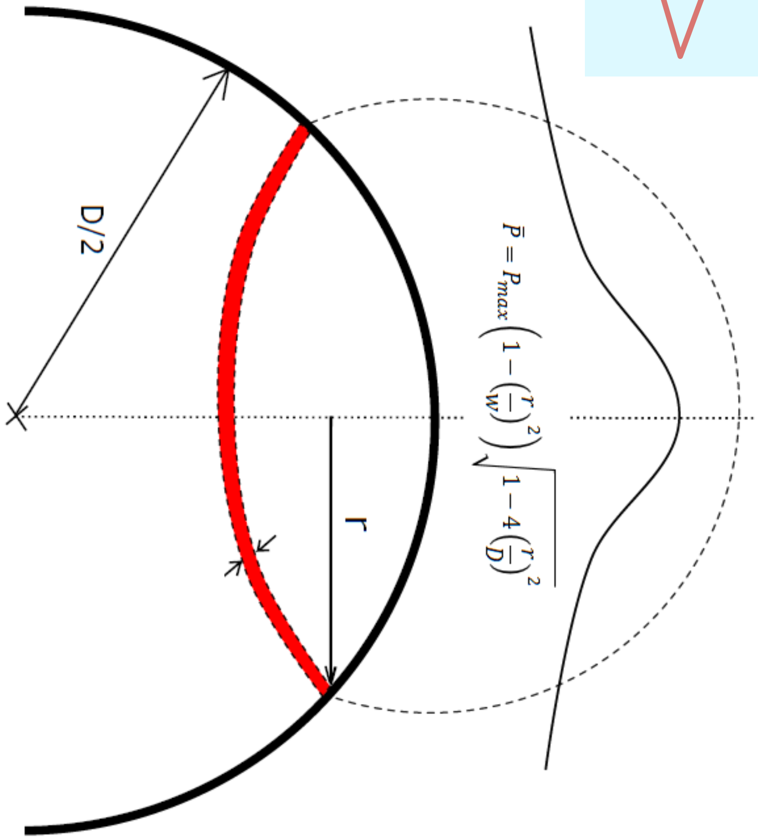


- Peak pressure on droplet surface:

$$\bar{P} = P_{max}\left(1 - \left(\frac{r}{w}\right)^2\right)\sqrt{1 - 4\left(\frac{r}{D}\right)^2}$$

- Ablation pressure**:

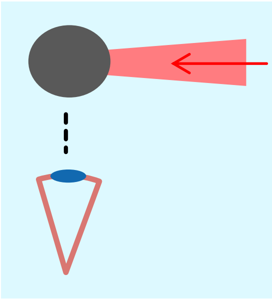
$$P_{max} \cong 8 \cdot {I_0}^{0.7} \Big/ \left(1 + \frac{l_{ac}^{(0)}\sin(\theta)}{w}{\tau_p}^{0.9}{I_0}^{0.3}\right)^{1.4}$$



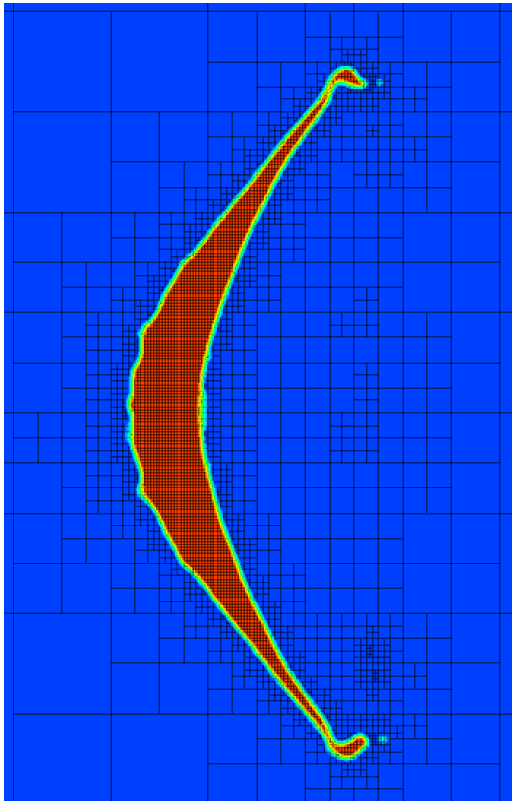
- $l_{ac}^{(0)}$ = nominal critical surface distance
- w = 1/e^2 beam waist radius
- P_{max} = peak ablation pressure
- I_0 = Laser Irradiance
- θ = ray convergence angle
- τ_p = laser pulse duration
- D = droplet diameter

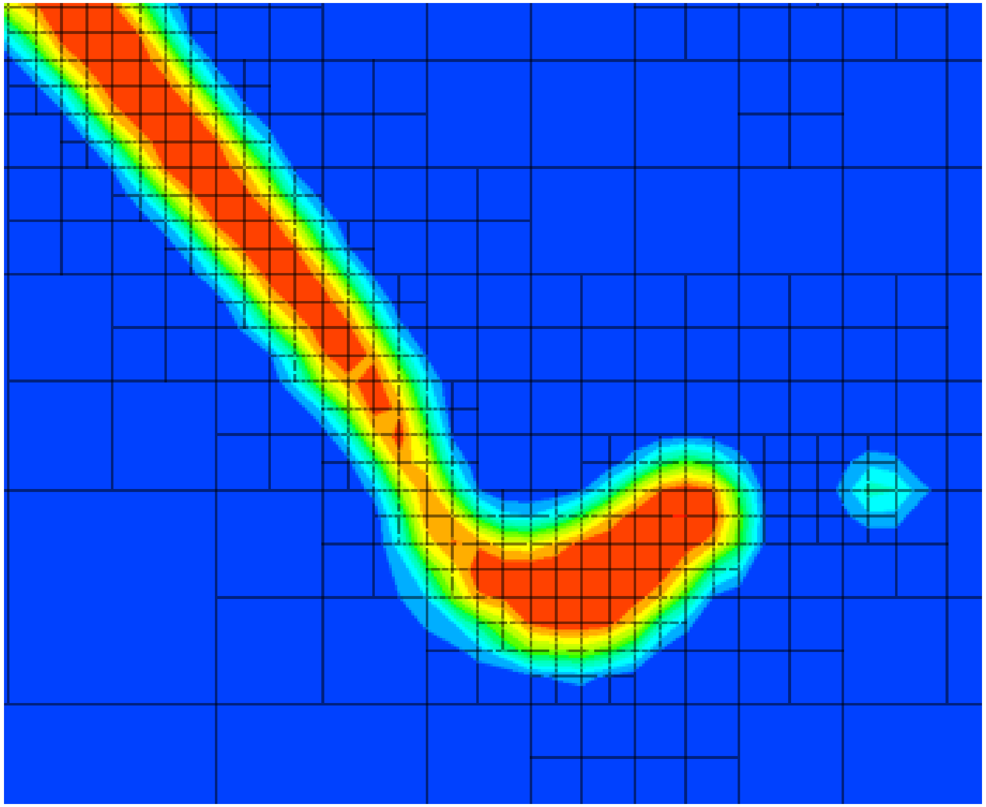
*Hudgins D, *et. al*., 2016 *J. Phys. D: Appl. Phys.* **49** 185205
Harrach R J, *et. al.*, 1982 *AIP Conf. Proc.* **78 164-8

High resolution meshing adapted around droplet fluid

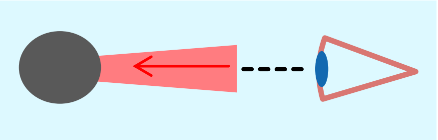


- Adaptive Meshing used in order to reduce computational costs of large domain/fluid volume ratio *O*(3)
- Mesh is adapted after every time step
- Mesh refined for cells with droplet fluid



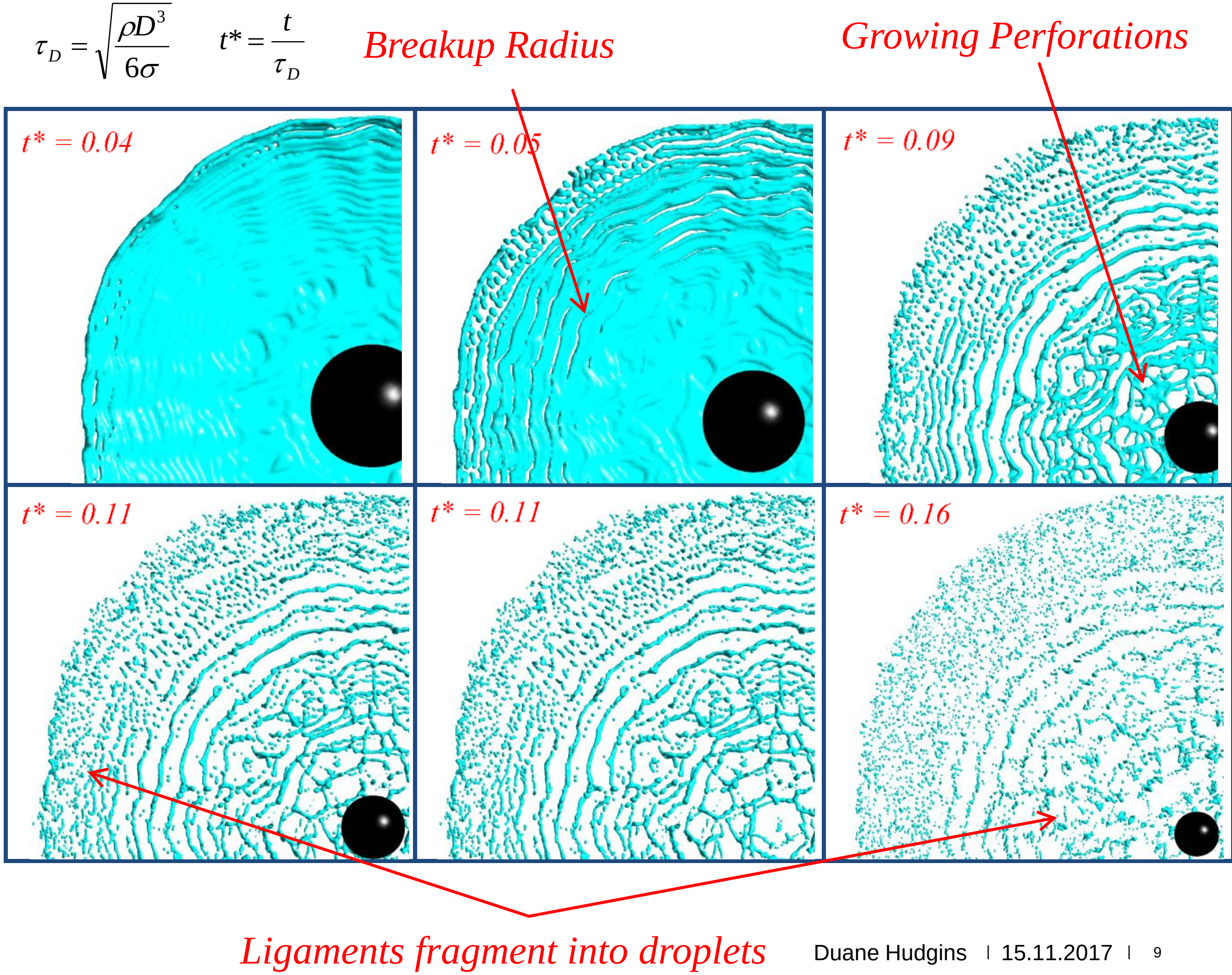


Simulated droplet fragments as expanding sheet



Simulations run until the fragments ceased dividing

$$\tau_D = \sqrt{\frac{\rho D^3}{6\sigma}} \qquad t^* = \frac{t}{\tau_D}$$



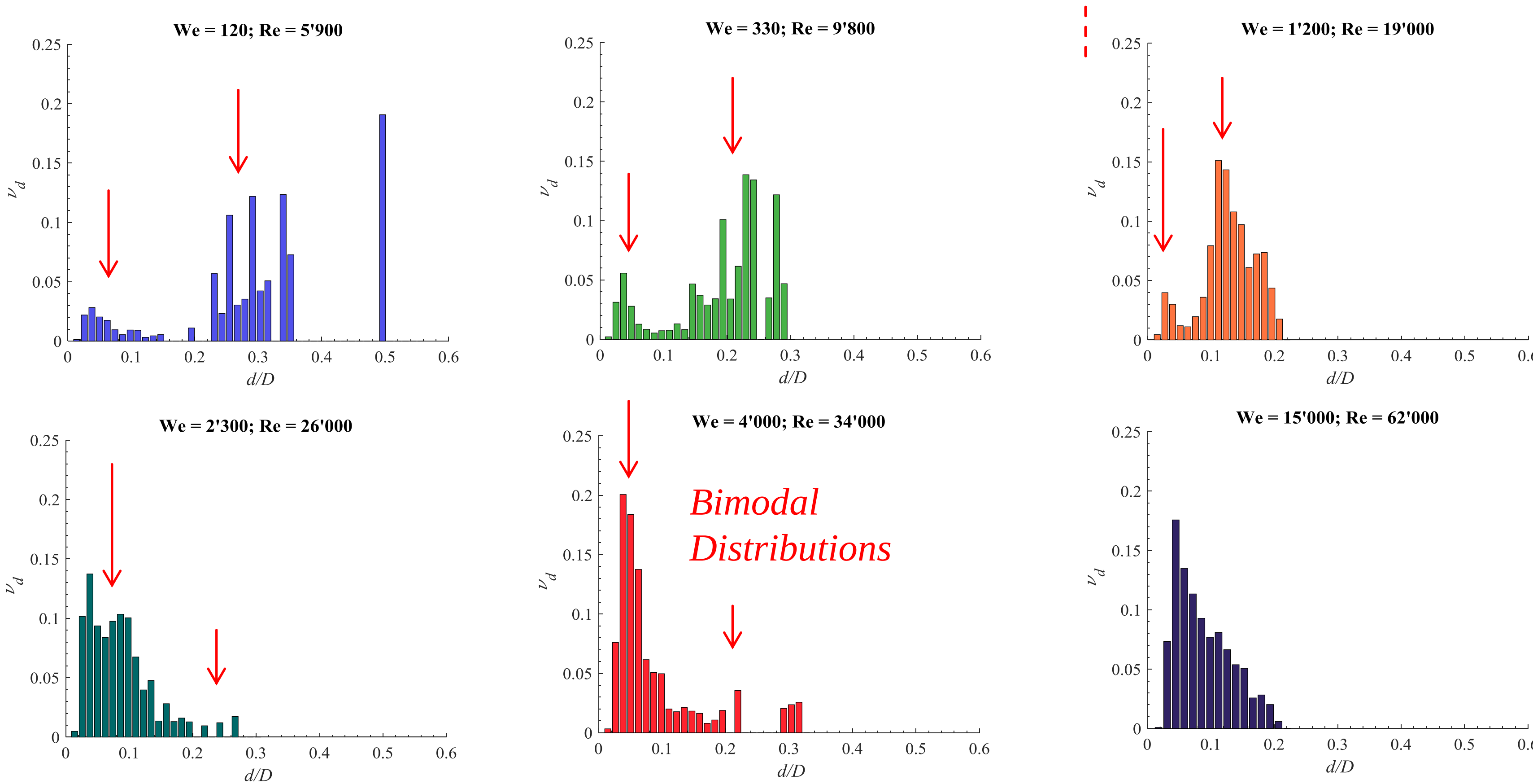
<u>Breakup Dynamics</u>

1) Droplet flattens into a circular sheet
2) Ligaments separate from rim at critical radius
3) Ligaments breakup into fragments
4) Smaller ligaments ejected first
5) Center of sheet grows holes, which expand into ligaments that fragment

Simulated fragment mass distributions show two breakup regimes

- Fragments sorted by size, position and velocity for analysis
- Splash regime is dominant at *We* > 1’000

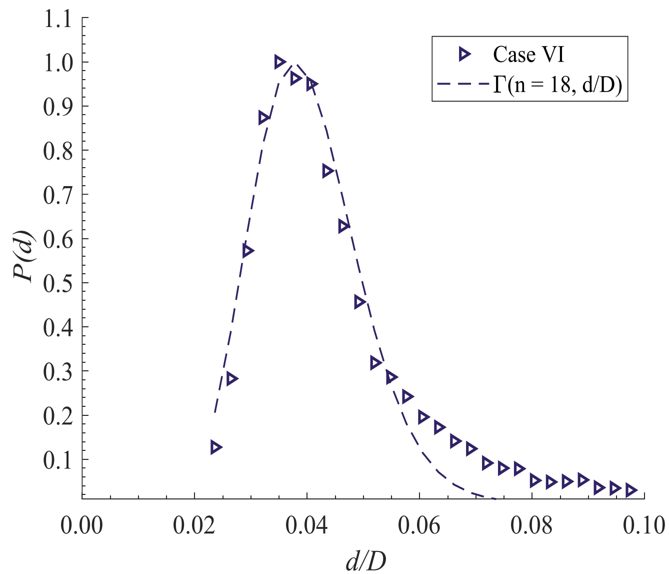
We > 1’000

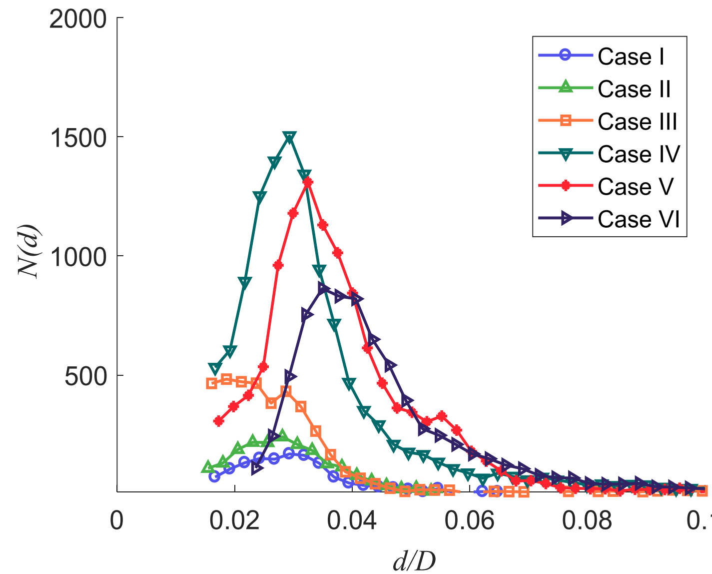


Simulated fragment size distributions indicate fragmentation from splashing rather than viscous sheet retraction

- Fragment size probability distribution functions (PDF) for fragment size for each case with a 95% confidence interval.
- PDF's for all cases emulate a *gamma* distribution*
- Parameter *n* calculated from the stretch rate *γ***
- Number of fragments increase with Weber number until fragment volume limit reached
- **Mean fragment diameter does not vary substantially with *We* indicating splashing, a process dominated by inertial/geometric influences**
- Broader size spectrum for higher *We* indicates lower stretch rate of original ligaments

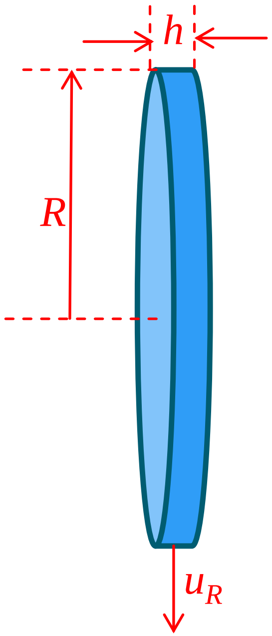
$$\Gamma\left(n, x = d/d_\Gamma\right) = \frac{n^n}{\Gamma(n)} x^{n-1} \cdot e^{-nx}$$





*Villermaux N *et. al.*, 2004 *Phys. Rev. Lett.* **92** 074501
Bremond N, *et. al.*, 2006 *J. Fluid Mech.* **549 273-306

Model of rim breakup matches well with CFD simulations



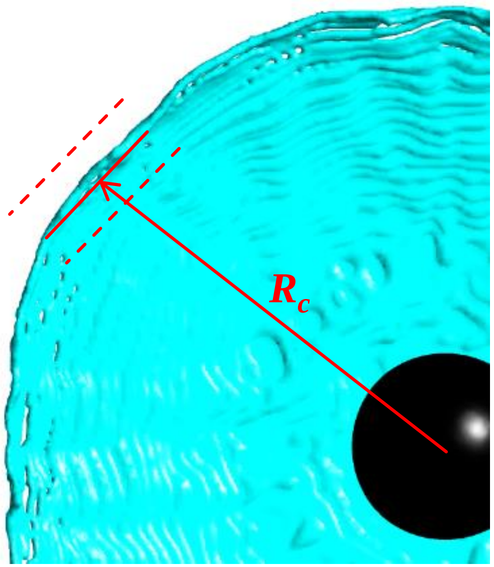
Critical Rim Radius R_c

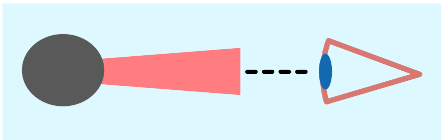
- Splash rim radius where ligaments detach from rim
- Rim thickness approximated as h
- Criteria for ligament pinch off is $\tau_c = \tau_s$ when the capillary time of the rim matches the stretch time
- $\tau_s < \tau_c$ for the period before the rim destabilization

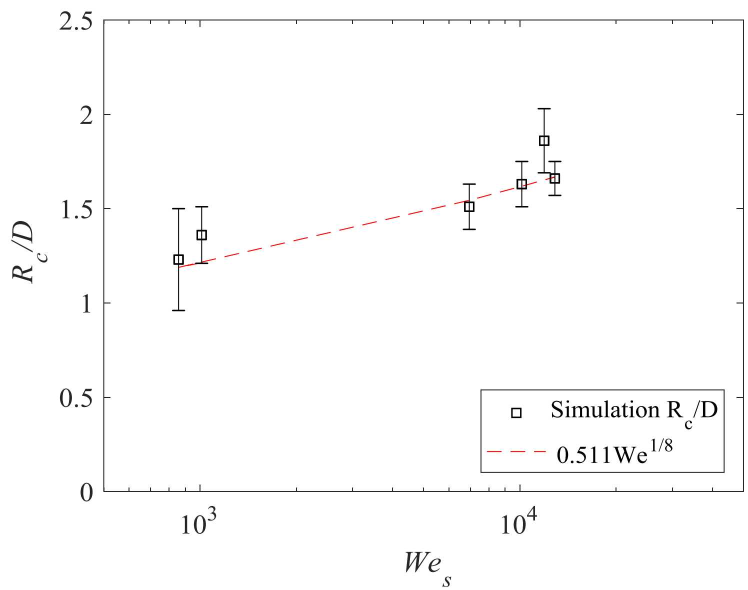
$$h = \frac{D^3}{6R^2}$$

$$\tau_c = \sqrt{\rho h^3 / \sigma}$$

$$\gamma = \frac{u_R}{R(t)} \qquad \tau_s = 1/\gamma$$







$$R_c = 0.511 \cdot D \cdot We_s^{1/8} \qquad We_s = \frac{\rho D u_R^2}{\sigma}$$

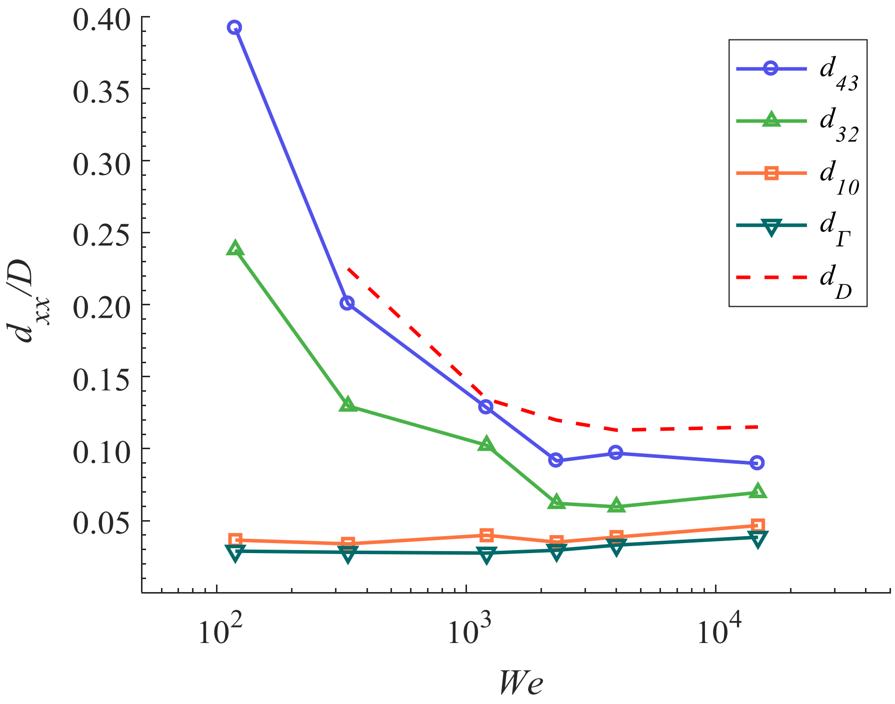
Model mean fragment diameter predictions match well with CFD simulations

- By assuming the ligament diameter is $d_L \sim h(R_c)$, the droplet diameter d_D can be approximated by the Dombrowski relation*
- For all cases the localized K value, defined as $K = Oh\, Re_s^{1.25}$ ranges from 400-2000
  - $d10/D \sim 0.04$ is consistent with previous experiments and models for droplets impacting a solid surface** where K >> 58

$$d_D = \left(\frac{3\pi}{\sqrt{2}}\right)^{1/3} d_L \left(1 + \frac{3\mu}{\sqrt{\rho\sigma d_L}}\right)^{1/2} \cong 1.88 d_L$$

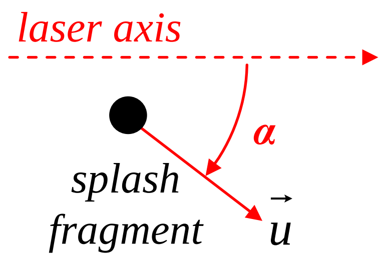
$$d_D \approx 1.21 \cdot D \cdot We_s^{-1/4}$$

$$d_{xy} = \frac{\sum_1^N d_i^x \upsilon_i}{\sum_1^N d_i^y \upsilon_i}$$



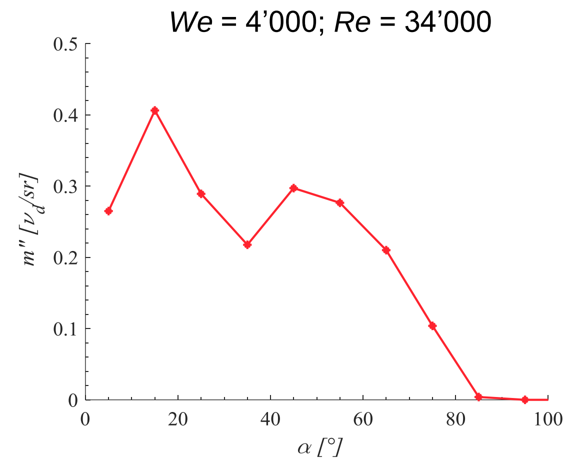
*Dombrowski N, *et. al.*, 1963 Chem. Eng. Sci. **18** 203-214
Mundo CHR, *et. al.*, 1995 Int. J. Multiph. Flow **21 151-173

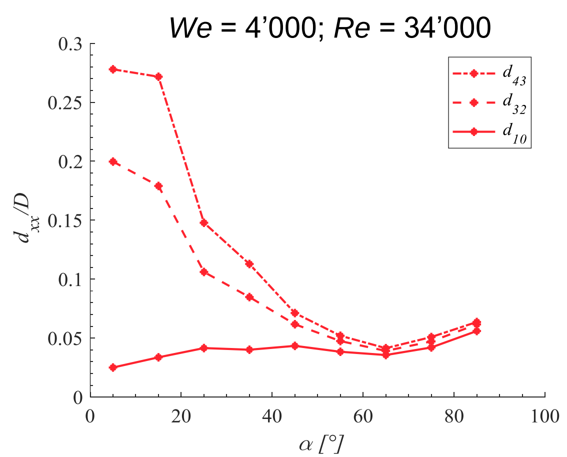
Fragment spatial distribution depends strongly on laser spot size



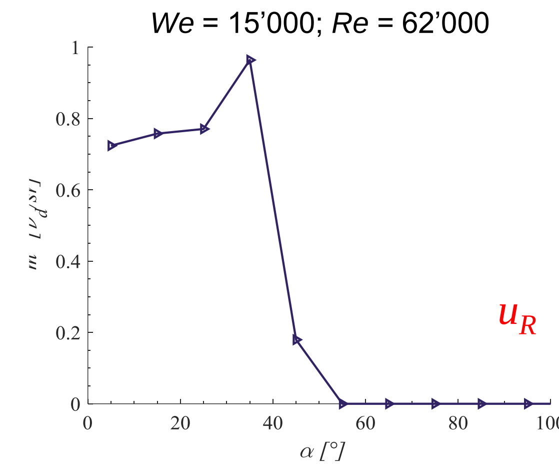
- Width of debris mass flux dependent on *w/D*
- Larger fragments distributed towards the center
- Narrowest distribution of fragments is towards the outside where the stretch is highest during breakup.

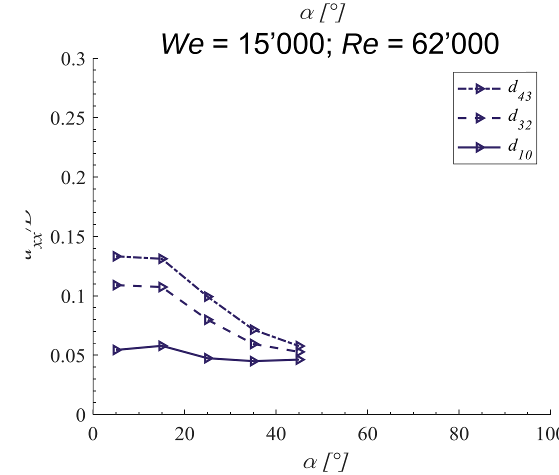
$$\boxed{\frac{w}{D} = 0.41}$$



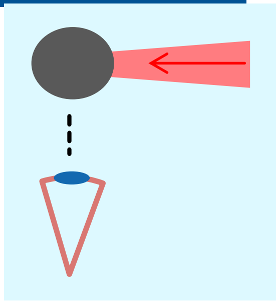


$$\boxed{\frac{w}{D} = 0.97}$$



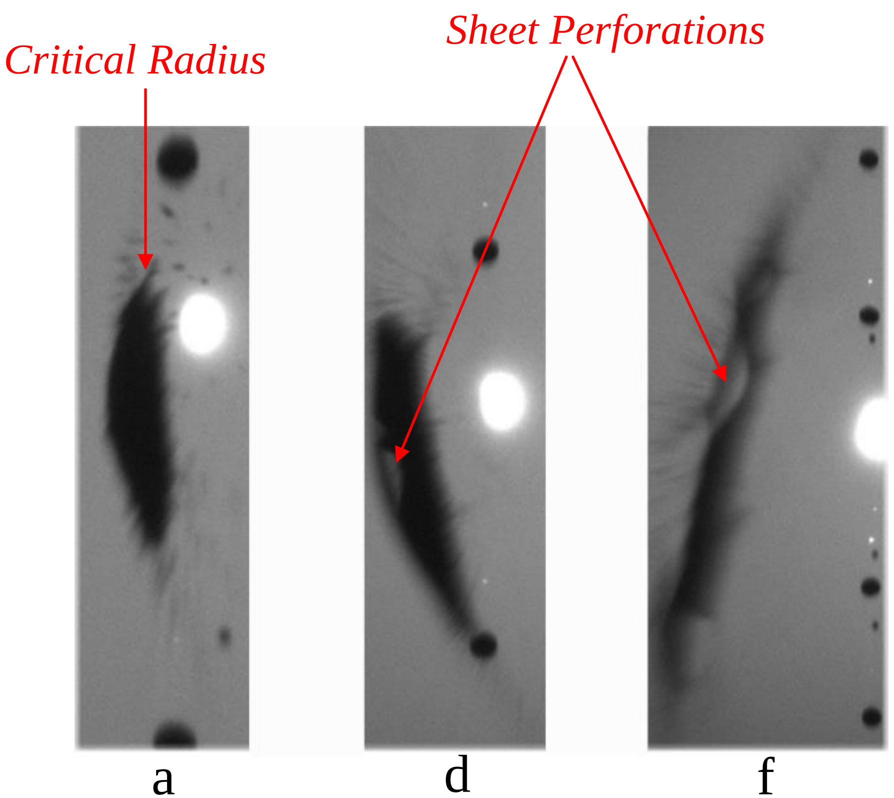


Simulation dynamics emulate phenomena observed experimentally



- Comparable cases performed experimentally*
- Critical radius is observed for lower *We* case
- At higher *We* holes are formed in middle of the sheet redistributing the stretch rate of the film

Case	a	d	f
We	80	770	3200
Re	5000	16000	32000
Oh		0.0019	
$\rho l/\rho v$		$\rightarrow \infty$	
$\mu l/\mu v$		48	
w/D		0.41	
log10(Ep)*	5.4	6.1	6.7
Ee*	78	390	1300
t of image*		0.43	



*Hudgins D, *et. al.*, 2016 *J. Phys. D: Appl. Phys.* **49** 185205

Conclusions

- Fluent VOF CFD simulations of the droplet breakup were used to determine the fundamental mechanisms governing neutral cluster fragment size and spatial distribution
- Large velocity gradients induced in the droplet lead to a high stretch rate of the expanding droplet sheet
- As the sheet thins, capillary destabilization causes perforations to form in the sheet that grow to form ligaments that fragment into droplets
- The droplet fragments scale as $d_D \approx 1.21 \cdot D \cdot We_s^{-1/4}$
- The analytical models are tools to estimate how system parameter changes in droplet size, laser pulse energy, positional stability, etc will influence the splash flux to the ML collector
- This model can be used to help determine an optimal positional range of the ML collector mirror
- Further work will focus on determining how the droplet shape irregularities and laser alignment influence the fragment sizes and debris spatial distribution

Acknowledgments

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